Top quark mass: Latest CDF results, Tevatron combination and electroweak implications

Costas Vellidis (on behalf of the CDF Collaboration)
Department of Physics, University of Athens, Athens 15771, Greece and Fermi National Accelerator Laboratory, Batavia, IL 60510, USA

A summary of the most up-to-date top quark mass measurements at CDF is presented. These analyses use top-antitop candidate events detected in the CDF experiment at the Tevatron collider with an integrated luminosity of up to ∼3/fb. The combination of all those measurements together with the corresponding top mass measurements from the concurrently running D0 experiment at the Tevatron yields a world average of $\mathrm{M_t} = [173.1 \pm 0.6(\mathrm{stat.}) \pm 1.1(\mathrm{syst.})]\ \mathrm{GeV/c^2}$.

1. Introduction

The top quark was discovered in 1995 at the Tevatron proton-antiproton collider at Fermilab by the CDF and D0 collaborations [1, 2]. The most intriguing aspect of the top quark is its mass. It is approximately 35 times the mass of the next most massive fermion, the b quark, and it is very close to the electroweak scale. Because of its mass, the top quark gives the largest contribution to loop corrections in the W boson propagator. Within the Standard Model (SM), the correlation between the top quark mass ($\mathrm{M_t}$) and the W boson mass induced by these corrections allows for setting limits on the mass of the yet undiscovered Higgs boson, and favor a relatively light Higgs.

According to the SM, at the Tevatron's 1.96 TeV center-of-mass energy top quarks are predominantly produced in pairs, by $\mathrm{q\overline{q}}$ annihilation in ∼85% of the cases and by gluon-gluon fusion in the remaining ∼15% [3]. Due to its very short life time, which in the SM is expected to be about 10^{-25} s, the top quark decays before hadronizing. In the SM the top quark decays into a W boson and a b quark in almost 100% of the cases. The W boson can decay either into quarks as a $\mathrm{q\overline{q}'}$ pair which subsequently hadronize or into a charged lepton-neutrino pair. This allows for a classification of the $\mathrm{t\overline{t}}$ candidate events into three non-overlapping samples, or decay channels, which are characterized by different final-state signatures, branching ratios (BRs), and background contaminations. The *all-hadronic* sample, where both W bosons decay hadronically, is characterized by six or more jets in the event (about 55% of the $\mathrm{t\overline{t}}$ events). The *lepton+jets* sample, where one W decays leptonically and the other hadronically, is characterized by one electron or muon, four or more jets, and large missing transverse energy $\not\!E_\mathrm{T}$ in the event (about 38% of the $\mathrm{t\overline{t}}$ events). The *dilepton* sample, where both W bosons decay leptonically, is characterized by two leptons, electrons or muons, two or more jets, and large $\not\!E_\mathrm{T}$ in the event (about 7% of the $\mathrm{t\overline{t}}$ events). The lepton+jets sample has the best compromise between statistics and background contamination. The dilepton sample is the cleanest at the cost of having the poorest statistics. The background contamination in all three samples can be greatly suppressed by "tagging" the jets associated with the b quarks. The most common tagging technique is based on the displacement of the reconstructed jet vertex from the event's primary vertex due to the relatively long life time of the b-flavored hadrons.

2. Top quark mass measurements

The top quark mass is a free parameter in the SM which can be directly measured at the Tevatron. Top mass measurements have been performed in each channel using a variety of methods. The best result has been achieved in the lepton+jets channel, due to its relatively high BR and moderate background. Recently a boost has been given to the mass accuracy by an innovative technique which exploits the hadronic products of the W decay in order to constrain the largest source of systematic uncertainty: the jet energy scale (JES). In this technique the mass of the two jets from the W decay is required to match the W mass, allowing for the so called "JES in situ" calibration. Thanks to this technique analyses in the all-hadronic sample have also achieved a better sensitivity than those in the dilepton channel. Complementary to this technique, new measurement methods have been recently applied which make use of only lepton or track-based information in the event and therefore are free of the JES systematic uncertainty.

Two general methods have been established to measure the top quark mass at the Tevatron. In the **Template Mehtod (TM)** distributions, or "templates", of variables strongly correlated with the top mass (most typical example is the event-by-event reconstructed top mass itself) are reconstructed on signal and background simulated events. In the **Matrix Element Mehtod (ME)** an event-by-event probability for signal and background is computed as a function of the top mass (for the signal only) and of the reconstructed observables. The ME method ex-

ploits all of the information in the event by making use of a leading order $t\bar{t}$ production matrix element, convoluted with parton distribution functions which model the structure of the colliding protons and transfer functions which are needed to step back from the reconstructed jets to the hadronizing partons. Both methods use a likelihood to compare data with the simulated events and extract the top mass. This likelihood is defined using a combination of signal and background templates (TM) or probabilities (ME), weighted according to the expected fraction of signal events in the data.

In the next subsections the top quark mass measurements reaching the highest sensitivity in CDF are described sample by sample. For brevity, not all of the measurements are reported in this paper.

2.1. Dilepton

The dilepton channel is characterized by a final-state signature of two high-P_T charged leptons (electrons or muons), two high-E_T b-jets, and large $\not\!\!E_T$ from the neutrinos. The largest amount of background comes from diboson events, Drelll-Yan events, and W+jets events where one jet fakes a charged-lepton signature. The signal-to-background (S/B) ratio is relatively high ($\sim$2 without b-tagging). The greatest challenge in this channel is the impossibility of "in situ" JES calibration. In addition, the kinematics is under-constrained due to the undetected neutrinos. The ME method deals with this issue by integrating over neutrino momenta while computing the event probability, whereas the top mass TM needs some assumptions to constrain the kinematics and reconstruct the event.

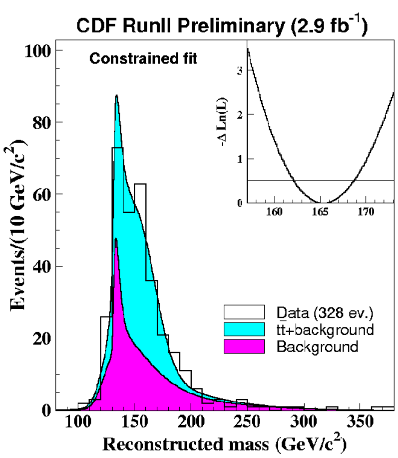

Figure 1: The likelihood fit of the neutrino ϕ weighting method which determines the top quark mass from dilepton events.

The most accurate CDF measurement in this channel is based on a ME method [4]. It exploits an evolutionary neural network (NN) optimized directly on the mass resolution rather than some intermediate or approximate figure of merit, such as the S/B ratio. The use of a NN improves by 20% the mass uncertainty compared to the previous analysis using the same method [5]. This measurement yields $M_t = [171.2 \pm 2.7(\text{stat.}) \pm 2.9(\text{syst.})]$ GeV/c^2 for an integrated luminosity of 2.9/fb. The TM is also used on the basis of an event-by-event top mass reconstruction [6]. The azimuthal angles of the neutrinos are integrated in order to constrain the kinematics, hence the method is named "neutrino ϕ weighting". The likelihood fit, shown in Figure 1, yields $M_t = [165.1^{+3.3}_{-3.2}(\text{stat.}) \pm 3.1(\text{syst.})]$ GeV/c^2 for an integrated luminosity of 2.8/fb.

2.2. Lepton+jets

The lepton+jets channel is characterized by a signature of a high-P_T electron or muon, four high-E_T jets, and high $\not\!\!E_T$. The background is mainly composed of W+jets events and multi-jet QCD events in which a jet is faking the signature of a charged lepton and $\not\!\!E_T$ comes from calorimeter mis-measurements. In order to enhance the S/B ratio from $\sim$0.5 to $\sim$4 and decrease the possible jet-to-parton assignments from 12 to 6 the presence of at least one b-tagged jet is usually required, with an efficiency of $\sim$55%.

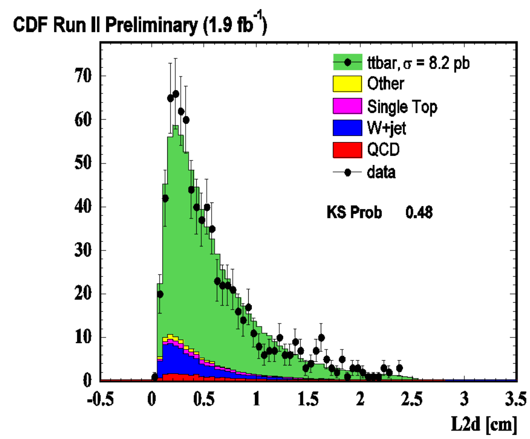

Figure 2: The fit of the L_{2d} signal and background templates which determines the top quark mass from lepton+jets events.

The most accurate CDF analysis applies the ME method with "in situ" JES calibration [7]. The method uses angular and energetic transfer functions while computing the event probability. The measurement yields $M_t = [172.1 \pm 1.1(\text{stat.} + \text{JES}) \pm 1.1(\text{syst.})]$ GeV/c^2 for an integrated luminosity of 3.2/fb. The b-JES remains the largest source of systematic uncertainty.

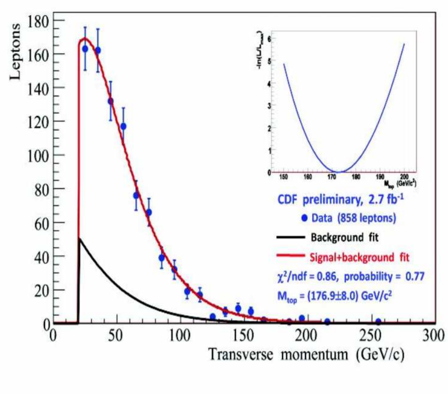

Figure 3: The likelihood fit of the lepton P_T signal and background distributions which determines the top quark mass from lepton+jets events.

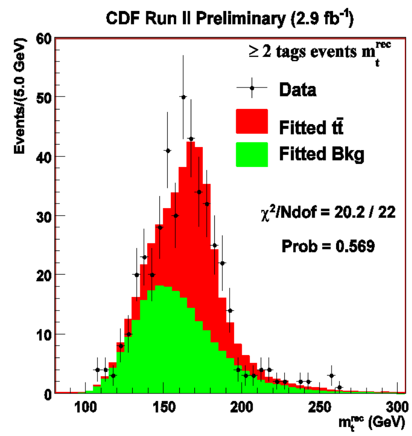

Figure 4: The fit of the top mass signal and background templates which determines the top quark mass from all-hadronic events.

Two novel TM techniques have been applied to CDF data making no direct use of jets for measuring the top quark mass. Both make use of kinematic variables sensitive to the top mass but insenstive to the JES. The one makes use of the tranverse decay length L_{xy} or L_{2d} of the b-tagged jets together with the transverse momentum P_T of the leptons and has been applied to 1.9/fb of lepton+jets data, yielding a result of $M_t = [175.3 \pm 6.2(\mathrm{stat.}) \pm 3.0(\mathrm{syst.})]$ GeV/c^2 [8]. Figure 2 shows the fit of the L_{2d} templates to the data. The other makes use of the transverse momentum P_T of the leptons only and has been applied to 2.8/fb of lepton+jets and dilepton data yielding a combined result of $M_t = [172.8 \pm 7.2(\mathrm{stat.}) \pm 2.3(\mathrm{syst.})]$ GeV/c^2 [9]. Figure 3 shows the fit of the lepton P_T distribution to the data in the lepton+jets channel only. Both techniques are fast and accurate candidates for the LHC, where the statistics will not limit the precision of the measurements.

2.3. All-hadronic

The all-hadronic channel is characterized by a signature of six high-E_T jets. Current analyses accept events with six to eight jets in the final state in order to include signal events with additional jets from initial or final state gluon radiation. At least one b-tagged jet is required. The all-hadronic sample is challenging because of the huge amount of QCD multi-jet background. For this reason NN are needed to optimize event selection in order to drastically enhance the S/B ratio from $\sim$1/400 up to $\sim$1/4.

So far only CDF has measured the top quark mass from this sample. The most sensitive analysis in this channel is a 2-dimensional TM [10]. Variables used to build templates are the event-by-event reconstructed top mass and the JES, which allows for for JES “in situ” calibration. This measurement uses a NN for event selection. This NN was recently upgraded to include also variables related with the jet shape for a better separation between gluon jets and light-quark jets from $t\bar{t}$ decays. Figure 4 shows the fit of the top mass signal and background templates which yields a result of $M_t = [174.8 \pm 2.4(\mathrm{stat.} + \mathrm{JES})^{+1.2}_{-1.0}(\mathrm{syst.})]$ GeV/c^2 with an integrated luminosity of 2.9/fb.

3. Tevatron combination, future perspective and electroweak implications

With the increasing integrated luminosity available at the Tevatron the systematic uncertainty has started dominating over the statistical uncertainty in the top quark mass measurements. The JES uncertainty remains the largest one among the various types of systematics. This is still the case in the lepton+jets and all-hadronic channels, despite the “in situ” JES calibration.

New analyses which follow a different approach to measure the top quark mass are now emerging in CDF and D0. Such are the b-jet transverse decay length and the lepton-P_T TM anayses described above. Even if these measurements do not reach a competitive statistical sensitivity, they are reported here because they are sensitive to different systematic uncertainties compared with the analyses directly involving jets.

Results from most of the analyses discussed above have been used to update the Tevatron top quark mass combination. Figure 5 summarizes the measurements included in the combination along with the Tevatron combined top quark mass of $M_t = [173.1 \pm 0.6(\mathrm{stat.}) \pm 1.1(\mathrm{syst.})]$ GeV/c^2, as of March 2009, which has a relative precision of 0.75%

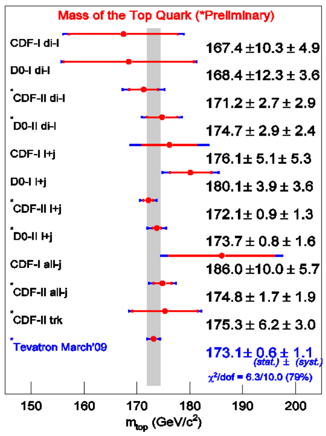

Figure 5: Projection of the CDF top quark mass uncertainty as a function of the Tevatron integrated luminosity.

[11]. CDF by itself has a top quark mass combination yielding $M_t = [172.6 \pm 0.9(\text{stat.}) \pm 1.2(\text{syst.})]$ GeV/c^2 [12]. The precision achieved is below 1%, already better than the Run II goal.

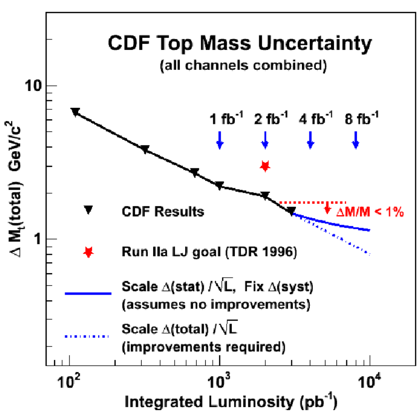

Figure 6: Projection of the CDF top quark mass uncertainty as a function of the Tevatron integrated luminosity.

The future perspective of CDF for the precision of the top quark mass measurements is shown in Figure 6. There the top mass total uncertainty (statistical plus systematic added in quadrature) is shown as a function of the Tevatron integrated luminosity, with the points representing the CDF top mass combined results which are obtained so far. The red dashed line above the last point represents the Run II goal of 1% relative total uncertainty. The continuous blue line beyond the last point is an extrapolation of the total uncertainty assuming that the statistical part will scale with the luminosity and the systematic part will remain constant, i.e. if no improvements will be made in the measurement methods. The blue dotted-dashed line beyond the last point is an extrapolation of the total uncertainty assuming that both the statistical and systematic parts will scale with the luminosity. This in turn assumes improvements such that only data driven sources of uncertainty (e.g. JES calibrations or fakes background estimates) will dominate the systematic uncertainty.

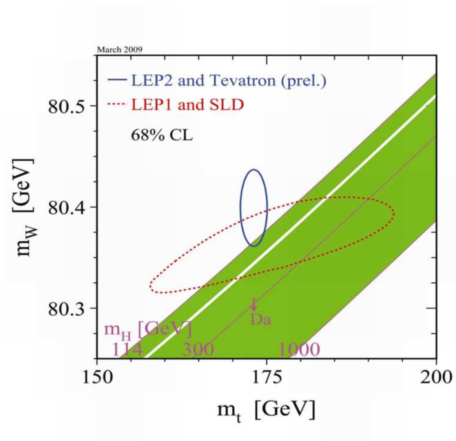

Figure 7: 1σ-level expectation for the SM Higgs boson mass derived from the measurements of the W boson and top quark masses.

The importance of the high precision of the top quark mass measurements achieved at the Tevatron for the localization of the SM Higss boson mass, as discussed in the Introduction, is shown in Figure 7. There the green band represents regions in the W mass vs. top mass plane corresponding to different values of the Higgs mass. The ellipsoids represent the expectation limits set on that plane by the measured W and top masses at the 1σ confidence level. The expectation arising from the latest Tevatron top mass measurement and the combined Tevatron and LEP2 W mass measurements [13] which is shown by the ellipsoid in continuous blue line points to a low Higgs mass, as mentioned in the Introduction. The improvement in the localization of the Higgs mass thanks to the Tevatron top mass precision is shown by comparing with the old expectation (red dashed line ellipsoid) for which the top mass was not yet measured but constrained instead by a global electroweak fit.

Acknowledgments

The author wishes to thank the CDF top-quark working group conveners for their help in preparing this presentation and the organizers of the "DPF 2009 Conference" for their hard work to set up the conference.

References

[1] F. Abe et al., (CDF Collaboration), *Phys. Rev. Lett.* **74**, 2626 (1995).

[2] S. Abachi et al., (D0 Collaboration), *Phys. Rev. Lett.* **74**, 2632 (1995).

[3] S. Abachi et al., JHEP **04**, 68 (2004); N. Kidonakis and R. Vogt, *Phys. Rev. D* **68**, 114014 (2003).

[4] A. Abulencia et al., (CDF Collaboration), *Phys. Rev. Lett.* **102**, 152001 (2009).

[5] A. Abulencia et al., (CDF Collaboration), *Phys. Rev. D* **75**, 031105 (2007).

[6] A. Abulencia et al., (CDF Collaboration), *Phys. Rev. D* **79**, 072005 (2008).

[7] CDF conference note 9692 (2009).

[8] CDF conference note 9414 (2008).

[9] CDF conference note 9881 (2009).

[10] CDF conference note 9694 (2009).

[11] Tevatron Electroweak Working Group, arXiv:0903.2503 (2009).

[12] CDF conference note 9714 (2009).

[13] Tevatron Electroweak Working Group, arXiv:0708.3642 (2007).